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Embodied energy and intensity in China's (normal and processing) exports and their driving forces, 2005–2015

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ARTICLE INFO

Article history:

Received 20 October 2019

Received in revised form 7 August 2020

Accepted 14 August 2020

Available online 29 August 2020

Keywords:

Input-output analysis

Energy embodied in trade

Aggregate embodied intensity

Structural decomposition analysis

Processing exports

China

JEL:

C67

P28

Q43

Q54

Q56

R15

ABSTRACT

International trade has important impacts on a country's energy consumption. This paper first uses the time-series (2005–2015) extended input-output database to study China's embodied energy and intensity in both normal and processing exports. Structural decomposition analysis (SDA) is then applied to analyze the driving forces behind the embodiment changes. The empirical results show that China's energy embodied in both normal and processing exports first increased in 2005–2008, dropped in 2009 due to the global financial crisis, and then rose again after 2009, and finally dropped in 2014–2015. The embodied energy in trade as a percentage of total energy consumption in China was relatively stable before and after the global financial crisis, at around 28% over the 2005–2008 period, and 22% over the 2009–2015 period. The contribution of the aggregate embodied intensity (AEI) of exports to China's aggregate energy intensity dropped from 30% in 2005 to 21% in 2015. Among China's trading partners, the United States, Japan and Korea together accounted for around half of China's embodied energy and AEI in exports in 2005, but their shares dropped to only one third in 2015. Energy efficiency improvement played the key role in reducing the embodied energy and intensity in China's exports. Similar analysis can be applied to other regions and indicators.

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1. Introduction

With global economic growth in the last few decades, the total energy consumption by all countries have increased by around half, from 6,268 Million tonnes of oil equivalent (Mtoe) in 1990 to 9,384 Mtoe in 2015 (IEA, 2017). Meanwhile, merchandise trade expanded by around four times, from USD 3,490 billion in 1990 to USD 16,537 billion in 2015 (WTO, 2018). In the last two decades, many studies have examined how international trade affects a country's energy consumption and related carbon emissions or “energy/emissions embodied in trade”, and results in “energy/carbon leakage” between developed and developing countries. For example, embodied emissions in trade were found to increase from 4.3 Gt CO₂ to 7.8 Gt CO₂ over the period 1990–2008 (Peters et al., 2011). Some countries and international organizations, e.g. the United Kingdom (UK, 2019) and the Organisation for Economic Co-operation and Development (OECD, 2019), have started

monitoring these embodiment flows and resulting consumption-based accounting, and discussed their implications to future energy and climate policy designs.

As the largest energy consumer and carbon emitter in the world, China has put forward several significant efforts to reduce energy consumption and carbon emissions. See, for example, the energy and emission target settings and accomplishments during its 11th Five Year Plan (2006–2010) and 12th Five Year Plan (2011–2015) periods (Price et al., 2011; Hu, 2016). In November 2014, “China's Energy Development Strategy Action Plan” was released by the Chinese government to provide guidelines for its energy developments during the 12th (2011–2015) and 13th (2016–2020) Five Year Plans (GOSC, 2014). As the world's manufacturing factory, significant amounts of China's energy/emissions are embodied in its exports. Consequently, China's energy efficiency improvements over time, especially during the 11th Five Year Plan (2006–2010) period, have greatly helped to reduce the embodied energy/emissions in its exports. It is important for China to monitor the changes of these embodiment flows and analyze the driving forces that brought about the changes.

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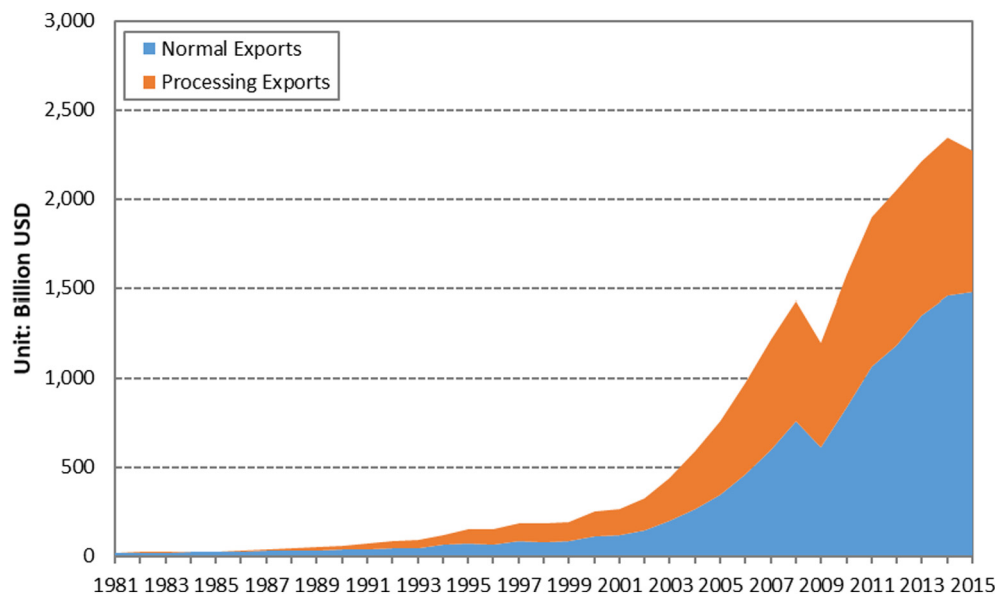


Fig. 1. China's normal and processing exports, 1981–2015. (Source: China Customs Statistical Yearbooks).

In the literature, there are many studies on China's embodied emissions at country level using the environmental input-output (I-O) framework (Leontief, 1970; Miller and Blair, 2009). Readers can refer to Su and Ang (2013), Sato (2014), Hawkins et al. (2015) and Zhang et al. (2017) for reviews of these studies and their findings for China. However, compared with embodied emissions, the number of studies on China's embodied energy are relatively few. Some studies have calculated China's energy embodied in exports using national I-O tables for selected years, such as Kahrl and Roland-Holst (2009) for years 1997, 2002 and 2004; Xu et al. (2009) for year 2002 and 2007; Liu et al. (2010) for years 1992, 1997, 2002 and 2005; Xie (2014) for year 1992, 1997, 2002, 2007 and 2010; Tang et al. (2016) for year 1997, 2002 and 2007; Zhang et al., 2016 for year 2002 and 2007; Yan and Su (2020a) for year 2010, 2012 and 2015. Other studies use multi-region I-O tables in the calculation for selected years. For example, Cui et al. (2015) use the GTAP database for year 2001, 2004 and 2007; Gao et al. (2018), Tao et al. (2018) and Zhang et al. (2019) use the WIOD database for year 2009; Wu and Chen (2017) and Wu et al. (2019) use the Eora database for year 2012. Only very few studies give time-series estimates, including Li et al. (2007) on total embodiment for period 1996–2004, Chen et al. (2011) on total embodiment for period 2001–2006, and Yang et al. (2014) on embodiment in bilateral trade between China and US for period 1997–2011. In addition, there are also studies using the structural decomposition analysis (SDA)¹ to investigate the driving forces behind the changes in embodied energy, such as Liu et al. (2010), Xie (2014), Tao et al. (2018), Deng et al. (2019) and Yan and Su (2020a).

China's international exports have an interesting feature that half are processing exports (see Fig. 1). In this study, processing exports are defined as the exports of the end products of assembling/processing imported intermediate inputs that are exempted from Chinese tariff and eventually sold overseas. On the other hand, normal exports are ordinary exports and are distinct from processing exports (Su et al., 2013). The energy/emissions embodied in per unit of processing exports are found to be much lower than those embodied in per unit of normal exports (Su et al., 2013; Jiang et al., 2015a). However, standard I-O tables

do not differentiate processing exports from normal exports. Therefore, it is necessary to construct “new” extended I-O tables and models, which is far more complicated than carrying out national and multi-regional embodiment analysis. As revealed in the report by WTO and IDE-JETRO (2011), some form of processing trade can be found in over 130 countries.

In the literature, there are a few studies using such extended I-O framework for China's embodied emission analysis, including Dietzenbacher et al. (2012) for year 2002, Su et al. (2013) for year 1997 and 2002, Xia et al. (2015) for year 2002 and 2007, Su and Thomson (2016) for year 2006–2012, Weitzel and Ma (2014), Jiang et al. (2015b), Liu et al., 2016b and Liu et al. (2017) for year 2007, Yan et al. (2020) for year 2002–2012, Zhang et al. (2020) for year 2012. However, there are only two studies using the extended framework on China's embodied energy, i.e. Jiang et al. (2015a) and Jiang et al. (2017) for year 2007. Among these studies, only three studies (Su et al., 2013; Xia et al., 2015; Su and Thomson, 2016) further apply the SDA technique to investigate the driving forces behind the embodiment changes in normal and processing exports.

In embodiment analysis, both the total embodiments and the embodiment intensities are useful to support policy makings. Most of the previous embodiment studies focus on the total embodiment, such as total embodied energy or emissions. Recently, Su and Ang (2017) propose the aggregate embodied intensity (AEI) concept by defining the AEI indicator as the ratio of embodied energy/emissions to embodied value added using the I-O framework. The AEI can be defined at the aggregate, final demand and sectoral levels (Su and Ang, 2017) or by transmission layer (Su et al., 2019) to analyze the relationship between energy/emissions and value added (or GDP) from the demand perspective. At the national level, the AEI in aggregate is equivalent to the aggregate intensity (AI) indicator. The AEI indicator at the higher level can be represented as a weighted sum of the AEI indicators at the lower level. It would be valuable to study the different AEI values of normal exports and processing exports in China using the extended I-O framework.²

This paper is an attempt to analyze China's embodied energy and intensity in normal and processing exports using the time-series

¹ See Su and Ang (2012a) and Wang et al. (2017a) for reviews of SDA studies applied to energy and emissions. Recent developments in SDA methodology include temporal aggregation (Su and Ang, 2012b), attribution analysis (Su and Ang, 2014a), different I-O forms of intensity indicator (Su and Ang, 2015), spatial-SDA (Su and Ang, 2016), processing trade (Su et al., 2013; Su and Thomson, 2016), and aggregate embodied intensity (Su and Ang, 2017; Su et al., 2019).

² For example, the AEI of emissions in exports are found to be higher than the national AI of emissions in China (Su and Ang, 2017), India (Zhu et al., 2018) and Singapore (Su and Ang, 2020). Recently, the national AEI framework has been further extended to the multi-region AEI framework within a country (Wang et al., 2020; Zhou et al., 2020).

Table 1

Structure of extended I-O table with processing trade and non-competitive imports.

| | | Intermediate transactions | | Final demands | | Total outputs |
|---------------------|---------------------------------|---------------------------------|--------------------|---------------|--------------------------|---------------|
| | | Domestic use and normal exports | Processing exports | Domestic | Exports | |
| Intermediate Inputs | Domestic use and normal exports | Z_{dd} | Z_{dp} | y_d | $y_{ne} = \sum y_{ne,k}$ | $x - y_{pe}$ |
| | Processing exports | 0 | 0 | 0 | $y_{pe} = \sum y_{pe,k}$ | y_{pe} |
| Imports | | Z_{id} | Z_{ip} | y_i | 0 | y_m |
| Value added | | v'_d | v'_p | | | |
| Total inputs | | $x' - y'_{pe}$ | y'_{pe} | | | |

(2005–2015) of Chinese extended I-O tables, and further investigate the driving forces behind the embodied energy/intensity changes using the SDA frameworks. The contributions of this paper include: (1) the national AEI framework has been extended from traditional I-O model to extended I-O model with normal/processing exports; (2) it gives the time-series (2005–2015) estimates of China's embodied energy in normal and processing exports by sector and major trading partners; (3) it investigates the driving forces to the changes of embodied energy in normal and processing exports in China using the additive SDA framework; (4) it shows the times-series (2005–2015) estimates of China's AEI indicators for normal and processing exports by sector and major trading partners; and (5) it analyzes the driving forces to the changes of AEI values in normal and processing exports in China using the multiplicative SDA framework.

The remaining sections of the paper will be organized as follows. Section 2 demonstrates how to derive embodied energy and intensity under an extended I-O framework and obtain the driving forces using the additive/multiplicative SDA frameworks. Section 3 presents the empirical study on China's embodied energy from 2005 to 2015. The final section summarizes the main findings and draws some key conclusions of the study.

2. Extended I-O framework

2.1. Energy embodied in normal and processing exports

Traditional I-O tables compiled by the Chinese National Department of Statistics are based on the competitive imports assumption, and do not differentiate the normal exports and processing exports. The study by Su and Ang (2013) firstly shows that the competitive imports assumption can in general overestimate a country's embodiment in trade and the non-competitive imports assumptions is advocated in embodiment studies. To support the analysis required in this paper, the extended I-O table with processing trade and non-competitive imports assumption is used as shown in Table 1. The extended I-O structure was introduced by Chen et al. (2001) when analyzing China's domestic employment and value added caused by the normal and processing exports. Recently, the extended I-O model has been applied to embodied energy/emission studies (e.g. Dietzenbacher et al., 2012; Su et al., 2013; Weitzel and Ma, 2014; Xia et al., 2015; Jiang et al., 2015a, 2015b; Liu et al., 2016b; Su and Thomson, 2016; Jiang et al., 2017; Liu et al., 2017).

The extended I-O model with processing trade and non-competitive imports assumption can be formulated as:

$$\begin{pmatrix} x - y_{pe} \\ y_{pe} \end{pmatrix} = \begin{pmatrix} Z_{dd} & Z_{dp} \\ 0 & 0 \end{pmatrix} \cdot 1 + \begin{pmatrix} y_d + y_{ne} \\ y_{pe} \end{pmatrix} \\ = \begin{pmatrix} A_{dd} & A_{dp} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} x - y_{pe} \\ y_{pe} \end{pmatrix} + \begin{pmatrix} y_d + y_{ne} \\ y_{pe} \end{pmatrix} \quad (1)$$

where x is the vector of total outputs, Z_{dd} is the matrix of domestic intermediate demands for domestic use and normal exports, Z_{dp} is the matrix of domestic intermediate demands for processing exports, y_d is the vector of domestic final demand, y_{ne} is the vector of normal exports, y_{pe} is

the vector of processing exports, $A_{dd} = Z_{dd} \cdot (\text{diag}(x - y_{pe}))^{-1}$ is the matrix of domestic production coefficients for domestic use and normal exports, and $A_{dp} = Z_{dp} \cdot (\text{diag}(y_{pe}))^{-1}$ is the matrix of domestic production coefficients for processing exports. Rearranging Eq. (1) leads to the following equation for I-O analysis with processing trade:

$$\begin{pmatrix} x - y_{pe} \\ y_{pe} \end{pmatrix} = \begin{pmatrix} I - A_{dd} & -A_{dp} \\ 0 & I \end{pmatrix}^{-1} \begin{pmatrix} y_d + y_{ne} \\ y_{pe} \end{pmatrix} \\ = \begin{pmatrix} (I - A_{dd})^{-1} & (I - A_{dd})^{-1} A_{dp} \\ 0 & I \end{pmatrix} \begin{pmatrix} y_d + y_{ne} \\ y_{pe} \end{pmatrix} \quad (2) \\ = \begin{pmatrix} L_{dd} & L_{dd} A_{dp} \\ 0 & I \end{pmatrix} \begin{pmatrix} y_d + y_{ne} \\ y_{pe} \end{pmatrix}$$

where $L_{dd} = (I - A_{dd})^{-1}$ represents the domestic Leontief inverse matrix for domestic use and normal exports.

With the energy intensity vectors $f_{v,d}$ and $f_{v,p}$ representing the energy consumption per unit of industry value added for domestic use/normal exports and processing exports respectively, the total amount of energy use in production can be formulated as

$$E_{tot} = E_{tot,d} + E_{tot,p} = \begin{pmatrix} f'_{v,d} & f'_{v,p} \end{pmatrix} \begin{pmatrix} v - v_{pe} \\ v_{pe} \end{pmatrix} \\ = \begin{pmatrix} f'_{v,d} & f'_{v,p} \end{pmatrix} \begin{pmatrix} \hat{k}_d & 0 \\ 0 & \hat{k}_p \end{pmatrix} \begin{pmatrix} x - y_{pe} \\ y_{pe} \end{pmatrix} \\ = \begin{pmatrix} f'_{v,d} & f'_{v,p} \end{pmatrix} \begin{pmatrix} \hat{k}_d & 0 \\ 0 & \hat{k}_p \end{pmatrix} \begin{pmatrix} L_{dd} & L_{dd} A_{dp} \\ 0 & I \end{pmatrix} \begin{pmatrix} y_d + y_{ne} \\ y_{pe} \end{pmatrix} \\ = \begin{pmatrix} f'_{v,d} & f'_{v,p} \end{pmatrix} \begin{pmatrix} \hat{k}_d L_{dd} & \hat{k}_d L_{dd} A_{dp} \\ 0 & \hat{k}_p \end{pmatrix} \left[\begin{pmatrix} y_d \\ 0 \end{pmatrix} + \begin{pmatrix} y_{ne} \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ y_{pe} \end{pmatrix} \right] \\ = f'_{v,d} \hat{k}_d L_{dd} y_d + f'_{v,d} \hat{k}_d L_{dd} y_{ne} + (f'_{v,d} \hat{k}_d L_{dd} A_{dp} + f'_{v,p} \hat{k}_p) y_{pe} \\ = E_d + E_{ne} + E_{pe} \quad (3)$$

where v and v_{pe} are the vectors of value added for total production and processing exports, $k_d = (\hat{x} - \hat{y}_{pe})^{-1} (v - v_{pe})$ and $k_p = (\hat{y}_{pe})^{-1} v_{pe}$ are the vectors of primary input coefficient for domestic use/normal exports and processing exports, $E_{tot,d} = f'_{v,d} (v - v_{pe})$ is the total energy use for domestic use and normal exports, $E_{tot,p} = f'_{v,p} v_{pe}$ is the total energy use for processing exports, $E_d = f'_{v,d} \hat{k}_d L_{dd} y_d$ is the energy embodied in domestic final demand, $E_{ne} = f'_{v,d} \hat{k}_d L_{dd} y_{ne}$ is the energy embodied in normal exports, and $E_{pe} = (f'_{v,d} \hat{k}_d L_{dd} A_{dp} + f'_{v,p} \hat{k}_p) y_{pe}$ is the energy embodied in processing exports.

2.2. Additive SDA of embodied energy changes

To analyze the absolute changes of embodied energy, additive SDA is more suitable than the multiplicative form. With the extended I-O model in Table 1 and embodied energy defined in Eq. (3), the

changes of embodied energy in normal exports and processing exports between t_1 and t_2 ($t_1 < t_2$) can be formulated as $\Delta E_{ne} = E_{ne}^{t_2} - E_{ne}^{t_1}$ and $\Delta E_{pe} = E_{pe}^{t_2} - E_{pe}^{t_1}$. Assuming n sectors in the traditional I-O table and m exporting countries/regions, the changes of embodied energy can be decomposed using the additive decomposition identity into five sub-effects as follows:

$$\begin{aligned} \Delta E_{ne}(t_1, t_2) &= E_{ne}^{t_2} - E_{ne}^{t_1} \\ &= \begin{pmatrix} f_{v,d}^{t_2} & f_{v,p}^{t_2} \end{pmatrix} \begin{pmatrix} \hat{k}_d^{t_2} L_{dd}^{t_2} & \hat{k}_d^{t_2} L_{dd}^{t_2} A_{dp}^{t_2} \\ 0 & \hat{k}_p^{t_2} \end{pmatrix} \begin{pmatrix} y_{ne}^{t_2} \\ 0 \end{pmatrix} \\ &\quad - \begin{pmatrix} f_{v,d}^{t_1} & f_{v,p}^{t_1} \end{pmatrix} \begin{pmatrix} \hat{k}_d^{t_1} L_{dd}^{t_1} & \hat{k}_d^{t_1} L_{dd}^{t_1} A_{dp}^{t_1} \\ 0 & \hat{k}_p^{t_1} \end{pmatrix} \begin{pmatrix} y_{ne}^{t_1} \\ 0 \end{pmatrix} \quad (4) \\ &= \bar{f}_v^{t_2} \cdot \bar{H}_d^{t_2} \cdot \bar{y}_{ne}^{t_2} - \bar{f}_v^{t_1} \cdot \bar{H}_d^{t_1} \cdot \bar{y}_{ne}^{t_1} \\ &= \bar{f}_v^{t_2} \cdot \bar{H}_d^{t_2} \cdot \bar{S}_{ne}^{t_2} \cdot \bar{r}_{ne}^{t_2} \cdot y_{tot,ne}^{t_2} - \bar{f}_v^{t_1} \cdot \bar{H}_d^{t_1} \cdot \bar{S}_{ne}^{t_1} \cdot \bar{r}_{ne}^{t_1} \cdot y_{tot,ne}^{t_1} \\ &= \Delta E_{eint,ne}(t_1, t_2) + \Delta E_{pstr,ne}(t_1, t_2) + \Delta E_{ysec,ne}(t_1, t_2) \\ &\quad + \Delta E_{yreg,ne}(t_1, t_2) + \Delta E_{ytot,ne}(t_1, t_2) \end{aligned}$$

$$\begin{aligned} \Delta E_{pe}(t_1, t_2) &= E_{pe}^{t_2} - E_{pe}^{t_1} \\ &= \begin{pmatrix} f_{v,d}^{t_2} & f_{v,p}^{t_2} \end{pmatrix} \begin{pmatrix} \hat{k}_d^{t_2} L_{dd}^{t_2} & \hat{k}_d^{t_2} L_{dd}^{t_2} A_{dp}^{t_2} \\ 0 & \hat{k}_p^{t_2} \end{pmatrix} \begin{pmatrix} 0 \\ y_{pe}^{t_2} \end{pmatrix} \\ &\quad - \begin{pmatrix} f_{v,d}^{t_1} & f_{v,p}^{t_1} \end{pmatrix} \begin{pmatrix} \hat{k}_d^{t_1} L_{dd}^{t_1} & \hat{k}_d^{t_1} L_{dd}^{t_1} A_{dp}^{t_1} \\ 0 & \hat{k}_p^{t_1} \end{pmatrix} \begin{pmatrix} 0 \\ y_{pe}^{t_1} \end{pmatrix} \quad (5) \\ &= \bar{f}_v^{t_2} \cdot \bar{H}_d^{t_2} \cdot \bar{y}_{pe}^{t_2} - \bar{f}_v^{t_1} \cdot \bar{H}_d^{t_1} \cdot \bar{y}_{pe}^{t_1} \\ &= \bar{f}_v^{t_2} \cdot \bar{H}_d^{t_2} \cdot \bar{S}_{pe}^{t_2} \cdot \bar{r}_{pe}^{t_2} \cdot y_{tot,pe}^{t_2} - \bar{f}_v^{t_1} \cdot \bar{H}_d^{t_1} \cdot \bar{S}_{pe}^{t_1} \cdot \bar{r}_{pe}^{t_1} \cdot y_{tot,pe}^{t_1} \\ &= \Delta E_{eint,pe}(t_1, t_2) + \Delta E_{pstr,pe}(t_1, t_2) + \Delta E_{ysec,pe}(t_1, t_2) \\ &\quad + \Delta E_{yreg,pe}(t_1, t_2) + \Delta E_{ytot,pe}(t_1, t_2) \end{aligned}$$

where $\bar{f}_v^t = (\bar{f}_{v,i}^t)_{2n \times 1}$ is the extended vector of energy intensity at time t , $\bar{H}_d^t = (\bar{H}_{d,ij}^t)_{2n \times 2n}$ is the extended matrix of domestic value added requirement at time t , $\bar{S}_{ne}^t = (\bar{S}_{ne,jk}^t)_{2n \times m}$ and $\bar{S}_{pe}^t = (\bar{S}_{pe,jk}^t)_{2n \times m}$ are the extended matrixes of normal and processing export's sectoral structures at time t , $\bar{r}_{ne}^t = (\bar{r}_{ne,k}^t)_{m \times 1}$ and $\bar{r}_{pe}^t = (\bar{r}_{pe,k}^t)_{m \times 1}$ are the extended vectors of normal and processing export's regional shares at time t , $y_{tot,ne}^t$ and $y_{tot,pe}^t$ are the total amounts of normal exports and processing exports at time t ; $\Delta E_{eint,\cdot}(t_1, t_2)$ is the additive energy intensity effect, $\Delta E_{pstr,\cdot}(t_1, t_2)$ is the additive production structure effect, $\Delta E_{ysec,\cdot}(t_1, t_2)$ is the additive final demand (export) sectoral structure effect, $\Delta E_{yreg,\cdot}(t_1, t_2)$ is the additive final demand (export) regional share effect, and $\Delta E_{ytot,\cdot}(t_1, t_2)$ is the additive total final demand (export) effect in the period between t_1 and t_2 ($t_1 < t_2$).

Using the LMDI-I approach (Ang et al., 2010; Ang, 2015; Su and Ang, 2012a), the effects in Eqs. (4-5) can be calculated as following

$$\Delta E_{eint,\cdot}(t_1, t_2) = \sum_{i,j,k} L(E_{i,jk}^{t_2}, E_{i,jk}^{t_1}) \ln \left(\frac{\bar{f}_{v,i}^{t_2}}{\bar{f}_{v,i}^{t_1}} \right) = \sum_i \Delta E_{eint,i}(t_1, t_2) \quad (6)$$

$$\Delta E_{pstr,\cdot}(t_1, t_2) = \sum_{i,j,k} L(E_{i,jk}^{t_2}, E_{i,jk}^{t_1}) \ln \left(\frac{\bar{H}_{d,ij}^{t_2}}{\bar{H}_{d,ij}^{t_1}} \right) = \sum_{i,j} \Delta E_{pstr,i,j}(t_1, t_2) \quad (7)$$

$$\Delta E_{ysec,\cdot}(t_1, t_2) = \sum_{i,j,k} L(E_{i,jk}^{t_2}, E_{i,jk}^{t_1}) \ln \left(\frac{\bar{S}_{i,jk}^{t_2}}{\bar{S}_{i,jk}^{t_1}} \right) = \sum_{j,k} \Delta E_{ysec,j,k}(t_1, t_2) \quad (8)$$

$$\Delta E_{yreg,\cdot}(t_1, t_2) = \sum_{i,j,k} L(E_{i,jk}^{t_2}, E_{i,jk}^{t_1}) \ln \left(\frac{\bar{r}_{i,jk}^{t_2}}{\bar{r}_{i,jk}^{t_1}} \right) = \sum_k \Delta E_{yreg,i,k}(t_1, t_2) \quad (9)$$

$$\Delta E_{ytot,\cdot}(t_1, t_2) = \sum_{i,j,k} L(E_{i,jk}^{t_2}, E_{i,jk}^{t_1}) \ln \left(\frac{y_{tot,i}^{t_2}}{y_{tot,i}^{t_1}} \right) \quad (10)$$

where $E_{i,jk}^t = \bar{f}_{v,i}^t \bar{H}_{d,ij}^t \bar{S}_{i,jk}^t \bar{r}_{i,jk}^t y_{tot,i}^t$ is the embodied energy from sub-category (i,j,k) , $L(a,b) = (a-b)/(\ln a - \ln b)$ is the logarithmic mean function, $\Delta E_{eint,i,\cdot}(t_1, t_2)$ is sector i 's additive energy intensity effect, $\Delta E_{pstr,i,\cdot}(t_1, t_2)$ is the additive production structure effect by sub-element $\bar{H}_{d,ij}$, $\Delta E_{ysec,j,\cdot}(t_1, t_2)$ is sector j and exporting country/region k 's additive final demand (exports) sectoral structure effect, $\Delta E_{yreg,i,j}(t_1, t_2)$ is country/region k 's additive final demand (exports) regional share effect. Detailed comparisons of different decomposition techniques in the context of additive SDA can be found in Su and Ang (2012a).

2.3. Aggregate embodied intensity in normal and processing exports

The AEI indicators proposed in Su and Ang (2017) can help the researchers and policy makers to better understand the relative energy/emission performance at different levels from the demand perspective. Similar as Eq. (3), for the I-O table with processing trade and non-competitive imports assumption, the total GDP value can be calculated using the production approach as³

$$\begin{aligned} GDP_{tot} &= GDP_{tot,d} + GDP_{tot,p} = \begin{pmatrix} k'_d & k'_p \end{pmatrix} \begin{pmatrix} x - y_{pe} \\ y_{pe} \end{pmatrix} \\ &= \begin{pmatrix} k'_d & k'_p \end{pmatrix} \begin{pmatrix} L_{dd} & L_{dd} A_{dp} \\ 0 & I \end{pmatrix} \begin{pmatrix} y_d + y_{ne} \\ y_{pe} \end{pmatrix} \\ &= \begin{pmatrix} k'_d & k'_p \end{pmatrix} \begin{pmatrix} L_{dd} & L_{dd} A_{dp} \\ 0 & I \end{pmatrix} \left[\begin{pmatrix} y_d \\ 0 \end{pmatrix} + \begin{pmatrix} y_{ne} \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ y_{pe} \end{pmatrix} \right] \quad (11) \\ &= k'_d L_{dd} y_d + k'_d L_{dd} y_{ne} + (k'_d L_{dd} A_{dp} + k'_p) y_{pe} \\ &= GDP_d + GDP_{ne} + GDP_{pe} \end{aligned}$$

where $GDP_{tot,d} = k'_d (x - y_{pe})$ is the total value added from domestic use and normal exports, $GDP_{tot,p} = k'_p y_{pe}$ is the total value added from processing exports, $GDP_d = k'_d L_{dd} y_d$ is the value added embodied in domestic final demand, $GDP_{ne} = k'_d L_{dd} y_{ne}$ is the value added embodied in normal exports, and $GDP_{pe} = (k'_d L_{dd} A_{dp} + k'_p) y_{pe}$ is the value added embodied in processing exports.

With the AEI definition given in Su and Ang (2017), the AEI in normal exports (AEI_{ne}) and processing exports (AEI_{pe}) can be formulated as following

$$\begin{aligned} AEI_{ne} &= \frac{E_{ne}}{GDP_{ne}} = \frac{f'_{v,d} \hat{k}_d L_{dd} y_{ne}}{k'_d L_{dd} y_{ne}} = \frac{f'_{v,d} \hat{k}_d L_{dd} \sum_k y_{ne,k}}{k'_d L_{dd} \sum_k y_{ne,k}} \\ &= \sum_k \frac{k'_d L_{dd} y_{ne,k}}{k'_d L_{dd} \sum_l y_{ne,l}} \cdot \frac{f'_{v,d} \hat{k}_d L_{dd} y_{ne,k}}{k'_d L_{dd} y_{ne,k}} \quad (12) \\ &= \sum_k w_{ne,k} \frac{E_{ne,k}}{GDP_{ne,k}} = \sum_k w_{ne,k} AEI_{ne,k} \end{aligned}$$

³ According to United Nations (1993), there are three approaches to calculate the GDP value, i.e. production, income and expenditure approaches. Both the production and expenditure approaches are commonly used in the I-O analysis, see Su and Ang et al. (2015) for example.

$$\begin{aligned}
AEI_{pe} &= \frac{E_{pe}}{GDP_{pe}} = \frac{(f'_{v,d} \hat{k}_d L_{dd} A_{dp} + f'_{v,p}) y_{pe}}{(k'_d L_{dd} A_{dp} + k'_p) y_{pe}} = \frac{(f'_{v,d} \hat{k}_d L_{dd} A_{dp} + f'_{v,p}) \sum_k y_{pe,k}}{(k'_d L_{dd} A_{dp} + k'_p) \sum_k y_{pe,k}} \\
&= \sum_k \frac{(k'_d L_{dd} A_{dp} + k'_p) y_{pe,k}}{(k'_d L_{dd} A_{dp} + k'_p) \sum_l y_{pe,l}} \cdot \frac{(f'_{v,d} \hat{k}_d L_{dd} A_{dp} + f'_{v,p}) y_{pe,k}}{(k'_d L_{dd} A_{dp} + k'_p) y_{pe,k}} \\
&= \sum_k w_{pe,k} \frac{E_{pe,k}}{GDP_{pe,k}} = \sum_k w_{pe,k} AEI_{pe,k}
\end{aligned} \quad (13)$$

where $y_{ne,k}$ is the normal export to country/region k , $y_{pe,k}$ is the processing export to country/region k , $AEI_{k,k}$ is the AEI in bilateral export with country/region k , $w_{ne,k}$ is the share of value added embodied in normal export to country/region k , $w_{pe,k}$ is the share of value added embodied in processing export to country/region k . The contribution of bilateral trade with country/region k to AEI can be calculated as $(w_{k,k} AEI_{k,k}) / AEI$, which is the same as their share of embodied energy in export.

According to Su and Ang (2017), the AEI in aggregate is the same as the total aggregate intensity (or $AI = E_{tot} / GDP_{tot} = AEI$). With Eqs. (3) and (11), the AEI in aggregate can be formulated as the weighted sum of the AEI at final demand category as

$$\begin{aligned}
AEI &= \frac{E_{tot}}{GDP_{tot}} = \frac{E_d + E_{ne} + E_{pe}}{GDP_d + GDP_{ne} + GDP_{pe}} \\
&= \frac{GDP_d}{GDP_{tot}} \cdot \frac{E_d}{GDP_d} + \frac{GDP_{ne}}{GDP_{tot}} \cdot \frac{E_{ne}}{GDP_{ne}} + \frac{GDP_{pe}}{GDP_{tot}} \cdot \frac{E_{pe}}{GDP_{pe}} \\
&= w_d AEI_d + w_{ne} AEI_{ne} + w_{pe} AEI_{pe}
\end{aligned} \quad (14)$$

where w is the share of value added embodied in special final demand, and AEI_d is the AEI in domestic final demand. The contribution of specific final demand to the AEI in aggregate can be calculated as $(w AEI) / AEI$, which is the same as their share of embodied energy in special final demand.

2.4. Multiplicative SDA of AEI changes

Multiplicative SDA is more suitable to analyze the relative changes in energy intensity. Using the general formula of multiplicative SDA in Su and Ang, 2015, the changes of AEI in normal and processing exports from $AEI \cdot t_1$ to $AEI \cdot t_2$ ($t_1 < t_2$) can be calculated as

$$\begin{aligned}
D_{tot,\bullet}(t_1, t_2) &= \frac{AEI_{\bullet}^{t_2}}{AEI_{\bullet}^{t_1}} = \frac{E_{\bullet}^{t_2} / GDP_{\bullet}^{t_2}}{E_{\bullet}^{t_1} / GDP_{\bullet}^{t_1}} = \left(\frac{E_{\bullet}^{t_2}}{E_{\bullet}^{t_1}} \right) / \left(\frac{GDP_{\bullet}^{t_2}}{GDP_{\bullet}^{t_1}} \right) = \frac{D_{\bullet,E}}{D_{\bullet,GDP}} \\
&= \left(\frac{\bar{f}_v^{t_2} \cdot \bar{H}_d^{t_2} \cdot \bar{S}_d^{t_2} \cdot \bar{r}_d^{t_2} \cdot y_{tot,\bullet}^{t_2}}{\bar{f}_v^{t_1} \cdot \bar{H}_d^{t_1} \cdot \bar{S}_d^{t_1} \cdot \bar{r}_d^{t_1} \cdot y_{tot,\bullet}^{t_1}} \right) / \left(\frac{\bar{1}' \cdot \bar{H}_d^{t_2} \cdot \bar{S}_d^{t_2} \cdot \bar{r}_d^{t_2} \cdot y_{tot,\bullet}^{t_2}}{\bar{1}' \cdot \bar{H}_d^{t_1} \cdot \bar{S}_d^{t_1} \cdot \bar{r}_d^{t_1} \cdot y_{tot,\bullet}^{t_1}} \right) \\
&= \left(\frac{\bar{f}_v^{t_2} \cdot \bar{H}_d^{t_2} \cdot \bar{S}_d^{t_2} \cdot \bar{r}_d^{t_2}}{\bar{f}_v^{t_1} \cdot \bar{H}_d^{t_1} \cdot \bar{S}_d^{t_1} \cdot \bar{r}_d^{t_1}} \right) / \left(\frac{\bar{1}' \cdot \bar{H}_d^{t_2} \cdot \bar{S}_d^{t_2} \cdot \bar{r}_d^{t_2}}{\bar{1}' \cdot \bar{H}_d^{t_1} \cdot \bar{S}_d^{t_1} \cdot \bar{r}_d^{t_1}} \right) \\
&= \frac{D_{eint,\bullet,E} \times D_{pstr,\bullet,E} \times D_{ysec,\bullet,E} \times D_{yreg,\bullet,E}}{D_{pstr,\bullet,GDP} \times D_{ysec,\bullet,GDP} \times D_{yreg,\bullet,GDP}} \\
&= D_{eint,\bullet,E} \times \left(\frac{D_{pstr,\bullet,E}}{D_{pstr,\bullet,GDP}} \right) \times \left(\frac{D_{ysec,\bullet,E}}{D_{ysec,\bullet,GDP}} \right) \times \left(\frac{D_{yreg,\bullet,E}}{D_{yreg,\bullet,GDP}} \right) \\
&= D_{eint,\bullet}(t_1, t_2) \times D_{pstr,\bullet}(t_1, t_2) \times D_{ysec,\bullet}(t_1, t_2) \times D_{yreg,\bullet}(t_1, t_2)
\end{aligned} \quad (15a)$$

or

$$\begin{aligned}
\ln D_{tot,\bullet}(t_1, t_2) &= \ln D_{eint,\bullet}(t_1, t_2) + \ln D_{pstr,\bullet}(t_1, t_2) \\
&\quad + \ln D_{ysec,\bullet}(t_1, t_2) + \ln D_{yreg,\bullet}(t_1, t_2)
\end{aligned} \quad (15b)$$

where $D_{eint,\bullet}(t_1, t_2)$ is the multiplicative energy intensity effect, $D_{pstr,\bullet}(t_1, t_2)$ is the multiplicative production structure effect, $D_{ysec,\bullet}(t_1, t_2)$ is the multiplicative final demand (export) sectoral structure effect, and

$D_{yreg,\bullet}(t_1, t_2)$ is the multiplicative final demand (export) regional share effect in the period between t_1 and t_2 ($t_1 < t_2$).

Using the LMDI-I approach (Ang et al., 2010; Ang, 2015; Su and Ang, 2012a), the effects in Eqs. (15a) and (15b) can be calculated as following

$$D_{eint,\bullet}(t_1, t_2) = \exp \left(\sum_{i,j,k} \frac{L(\bar{E}_{ijk}^{t_2}, \bar{E}_{ijk}^{t_1})}{L(\bar{E}_{ijk}^{t_2}, \bar{E}_{ijk}^{t_1})} \ln \left(\frac{\bar{f}_{v,i}^{t_2}}{\bar{f}_{v,i}^{t_1}} \right) \right) \quad (16)$$

$$D_{pstr,\bullet}(t_1, t_2) = \frac{\exp \left(\sum_{i,j,k} \frac{L(\bar{E}_{ijk}^{t_2}, \bar{E}_{ijk}^{t_1})}{L(\bar{E}_{ijk}^{t_2}, \bar{E}_{ijk}^{t_1})} \ln \left(\frac{\bar{H}_{d,ij}^{t_2}}{\bar{H}_{d,ij}^{t_1}} \right) \right)}{\exp \left(\sum_{i,j,k} \frac{L(\bar{GDP}_{ijk}^{t_2}, \bar{GDP}_{ijk}^{t_1})}{L(\bar{GDP}_{ijk}^{t_2}, \bar{GDP}_{ijk}^{t_1})} \ln \left(\frac{\bar{H}_{d,ij}^{t_2}}{\bar{H}_{d,ij}^{t_1}} \right) \right)} \quad (17)$$

$$D_{ysec,\bullet}(t_1, t_2) = \frac{\exp \left(\sum_{i,j,k} \frac{L(\bar{E}_{ijk}^{t_2}, \bar{E}_{ijk}^{t_1})}{L(\bar{E}_{ijk}^{t_2}, \bar{E}_{ijk}^{t_1})} \ln \left(\frac{\bar{S}_{jk}^{t_2}}{\bar{S}_{jk}^{t_1}} \right) \right)}{\exp \left(\sum_{i,j,k} \frac{L(\bar{GDP}_{ijk}^{t_2}, \bar{GDP}_{ijk}^{t_1})}{L(\bar{GDP}_{ijk}^{t_2}, \bar{GDP}_{ijk}^{t_1})} \ln \left(\frac{\bar{S}_{jk}^{t_2}}{\bar{S}_{jk}^{t_1}} \right) \right)} \quad (18)$$

$$D_{yreg,\bullet}(t_1, t_2) = \frac{\exp \left(\sum_{i,j,k} \frac{L(\bar{E}_{ijk}^{t_2}, \bar{E}_{ijk}^{t_1})}{L(\bar{E}_{ijk}^{t_2}, \bar{E}_{ijk}^{t_1})} \ln \left(\frac{\bar{r}_{jk}^{t_2}}{\bar{r}_{jk}^{t_1}} \right) \right)}{\exp \left(\sum_{i,j,k} \frac{L(\bar{GDP}_{ijk}^{t_2}, \bar{GDP}_{ijk}^{t_1})}{L(\bar{GDP}_{ijk}^{t_2}, \bar{GDP}_{ijk}^{t_1})} \ln \left(\frac{\bar{r}_{jk}^{t_2}}{\bar{r}_{jk}^{t_1}} \right) \right)} \quad (19)$$

where $\bar{E}_{ijk}^t = \bar{f}_{v,i}^t \bar{H}_{d,ij}^t \bar{S}_{jk}^t \bar{r}_{jk}^t$, $\bar{E}_{ijk}^t = \sum \bar{E}_{ijk}^t$, $\bar{GDP}_{ijk}^t = \bar{H}_{d,ij}^t \bar{S}_{jk}^t \bar{r}_{jk}^t$, and $\bar{GDP}_{ijk}^t = \sum \bar{GDP}_{ijk}^t$. The aggregate decomposition effects at the sectoral level can be obtained through the attribution analysis of the LMDI index (Choi and Ang, 2012) or the generalized Fisher index (Su and Ang, 2014a). For example, the multiplicative energy intensity effect in Eq. (16) can be further decomposed using the attribution analysis as

$$\begin{aligned}
\ln D_{eint,\bullet}(t_1, t_2) &= \sum_i \bar{w}_i \ln \left(\frac{\bar{f}_{v,i}^{t_2}}{\bar{f}_{v,i}^{t_1}} \right) = \sum_i \ln \left(\frac{\bar{f}_{v,i}^{t_2}}{\bar{f}_{v,i}^{t_1}} \right)^{\bar{w}_i} \\
&= \sum_i \ln D_{eint,i}(t_1, t_2)
\end{aligned} \quad (20)$$

where $D_{eint,i}(t_1, t_2)$ is sector i th energy intensity change effect, and \bar{w}_i is the weighted share obtained from the attribution analysis.

3. Empirical study

3.1. Data and assumptions

The 2018 version of the OECD Inter-Country Input-Output (ICIO) database (OECD, 2018) was used in the analysis. The OECD-ICIO database is the multi-region I-O tables, compiled based on the SNA08 statistics and using an ISIC Rev.4 industry list. It covers 65 regions and 36 sector classifications (see Tables A.1 and A.2 in Appendix A) for period 2005–2015.⁴ China's activities are divided into activities associated with the processing exports and those excluding the processing exports. Thus, China's exports (both normal and processing exports) can be further

⁴ For the embodied energy/emission flows, two commonly used approaches are EEBT and MRIO approaches (Peters, 2008; Su and Ang, 2011). However, the EEBT approach is more convenient for trade policy analysis, while the MRIO approach can capture the feedback effects but is much more complicated and includes more uncertainties in constructing the global MRIO tables. This paper uses the EEBT approach when measuring the embodied energy in China's processing and normal exports to world countries.

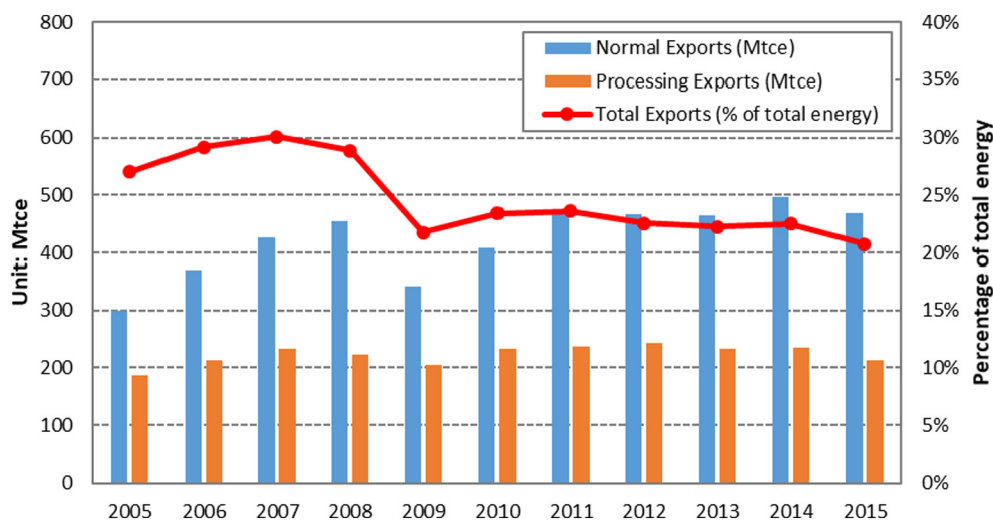
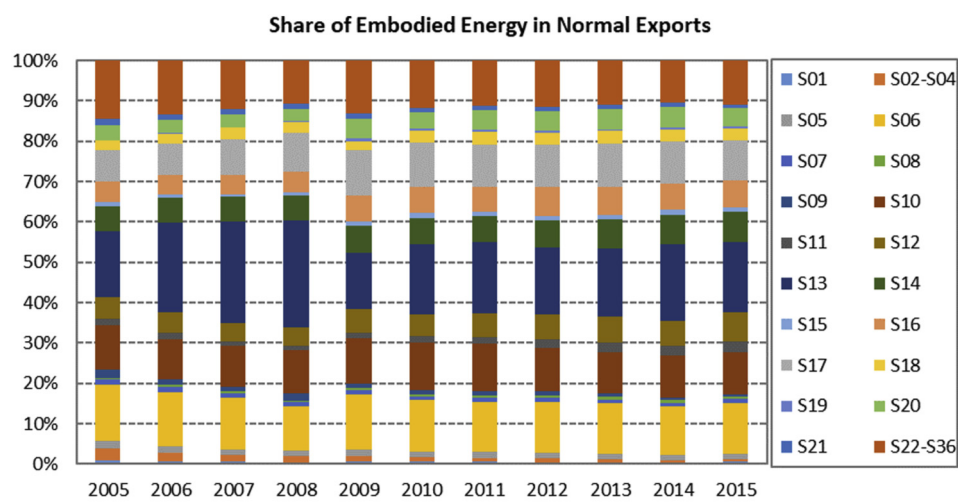
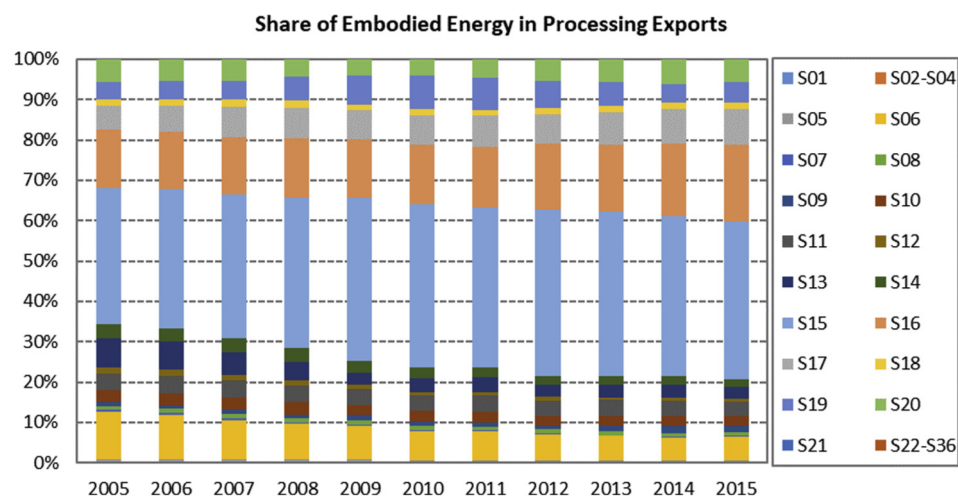


Fig. 2. China's energy embodied in exports and their contributions to national total energy consumption, 2005–2015.



(a) Normal exports



(b) Processing exports

Fig. 3. Share of China's embodied energy in exports by sector, 2005–2015. (Note: The detailed sector names are given in Table A.1 in Appendix A, and the detailed results of the plots can be found in the supplemental data file).

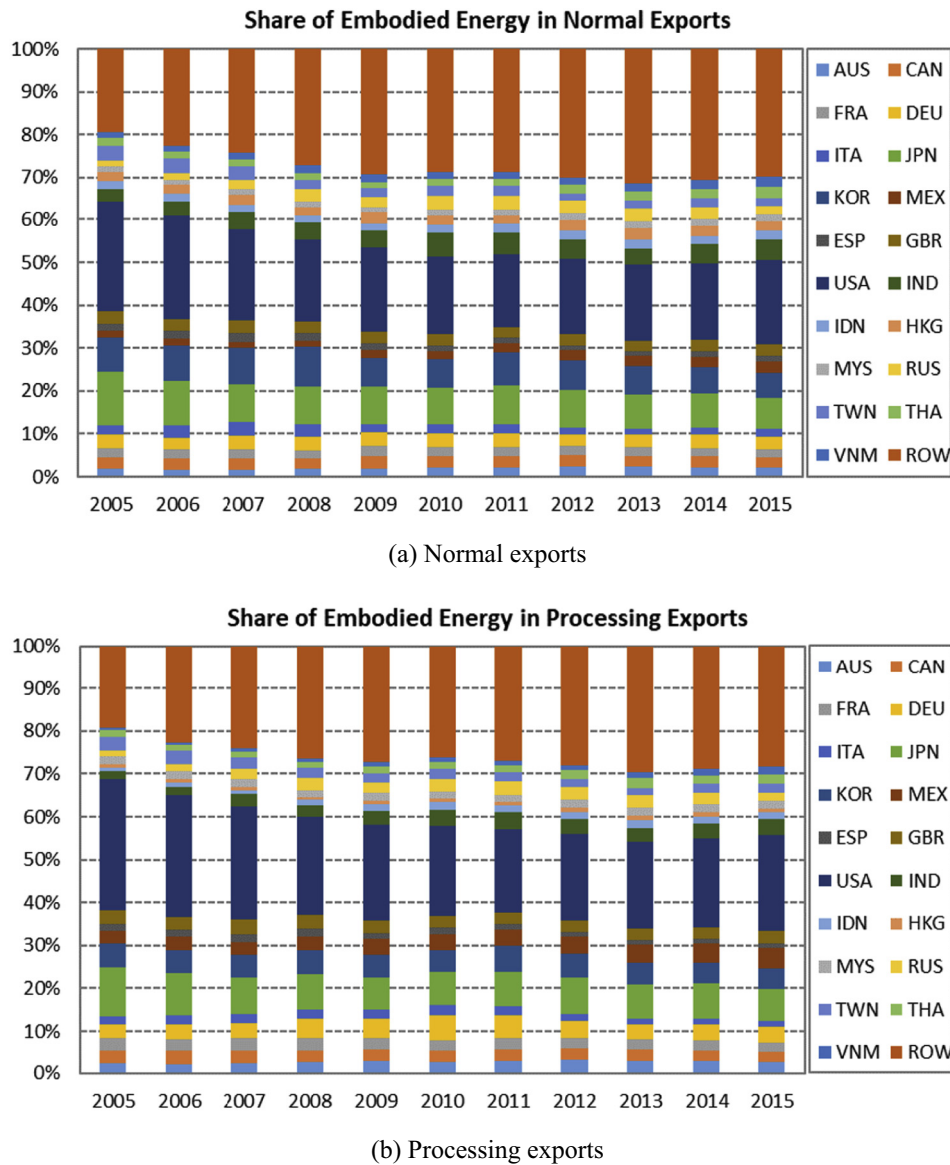


Fig. 4. Share of China's embodied energy in exports with trading partners, 2005–2015. (Note: The detailed region names are given in Table A.2 in Appendix A, and the detailed results of the plots can be found in the supplemental data file).

disaggregated into bilateral trades with 64 trading partners. China's extended I-O table compilations used the data from customs statistics (GAC, 2006–2016) and other statistical yearbooks (NBS, 2006b, 2006c, 2006d). All the values were deflated to the constant 2010 price using the price index given in the China Price Statistical Yearbooks (NBS, 2006e).

China's sectoral energy consumption data were obtained from China's Energy Statistical Yearbooks (NBS, 2006a). There are 20 energy types in the energy database, including raw coal, cleaned coal, washed coal, briquettes, coke, coke oven gas, other gas, coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, refinery gas, other petroleum products, natural gas, heat, electricity and other energy. Different energy types were converted into the tonnes of standard coal equivalent (tce) based on the conversion factors provided in NBS (2006a). The "data treatment scheme 2" proposed in Su et al. (2010) was used to match the sectoral energy data with the I-O classification to ensure comparability. Following the data treatments in Su et al. (2013) and Su and

Thomson (2016), the energy intensities for processing exports were assumed to be the same as the representative processing trade regions (such as Guangdong, Fujian and Jiangsu provinces) in China. The detailed steps for estimating the sectoral energy consumption at China's regional level are given in the Appendix A in Su and Ang, 2010. The final extended I-O tables for China have 72 sectors for period 2005–2015.

3.2. China's energy embodied in trade, 2005–2015

The time-series extended I-O tables enables the embodied energy in normal and processing exports for the 2005–2015 period to be obtained using Eq. (3). The embodiment results for normal and processing exports, as well as the percentage of embodied energy in total exports against China's total energy consumption, are given in Fig. 2. Embodied energy in normal/processing exports by sector and by trading partner are given in Figs. 3 and 4, respectively (detailed sectoral and regional names are given in Tables A.1 and A.2 in Appendix A).

For ease of illustration, the sectoral results in Fig. 3 are aggregated into 20 sectors, and the bilateral regional results in Fig. 4 are also aggregated into 20 regions⁵.

The overall trend in Fig. 3 shows that the embodied energy in both normal and processing exports increased until the global financial crisis in 2007–2008. Processing exports was more sensitive to the crisis, and responded with a decrease immediately in 2008. Normal exports continued to increase in 2008 with inertia, but dramatically dropped in 2009. The embodiments in both types of exports rose again after 2009, remained relatively stable during 2011–2013, and finally dropped at the end of China's 12th FYP in 2014–2015. The energy embodied in normal exports were around 300–500 million tonnes of standard coal equivalent (Mtce), and those embodied in process exports were around 190–240 Mtce. In comparison, the percentage of energy embodied in total exports against national total energy consumption was quite stable before and after the global financial crisis, respectively. It was around 29% for period 2006–2008, and some 23% for the 2010–2014 period.

Some interesting patterns are observed from the results at the sectoral level. For normal exports as shown in the Fig. 3(a), the major shares of embodied energy came from sectors “S13-Basic metals” (16%–26%), “S06-Textiles, wearing apparel, leather and related products” (12%–14%), “S10-Chemicals and pharmaceutical products” (10%–11%), and “S17-Machinery and equipment” (8%–11%). The share of sector “S13-Basic metals” dropped significantly around the global financial crisis, from 26.5% in 2008 to only 13.9% in 2009; in contrast, the share of sector “S06-Textiles, wearing apparel, leather and related products” and sector “S17-Machinery and equipment” relatively increased.

For processing exports as shown in Fig. 3(b), the embodied energy was mainly from sectors “S15-Computer, electronic and optical products” (34%–40%), “S16-Electrical equipment” (14%–19%), and “S06-Textiles, wearing apparel, leather and related products” (6%–12%). Different from the processing exports, the share of embodied energy in these major sectors did not change that much during the global financial crisis. Overall speaking, there was a shift from light manufacturing to equipment manufacturing, especially for “S16-Electrical equipment” and “S17-Machinery and equipment”.

It is also interesting to find some trends in China's embodied energy in bilateral trade. For normal exports as shown in the Fig. 4(a), the major shares of embodied energy were with the United States (17%–25%), Japan (7%–12%) and Korea (6%–9%). Most of the regional share decreased in 2009 with a time lag, but the share of the United States where the global financial crisis originated dropped earlier from 2007. For processing exports as shown in the Fig. 4(b), the major shares of embodied energy were with the United States (19%–30%), Japan (7%–12%), Korea (5%–6%) and Germany (3%–6%). Overall speaking, there were significant shifts from the United States, Japan and Korea to the other economies in the rest of the world.

3.3. Additive SDA of embodied energy changes, 2005–2015

The changes in embodied energy as discussed in Section 3.2 were driven by many factors, such as the energy efficiency improvement/deterioration and export demand increase/decrease. To better understand the driving forces behind the changes in embodied energy, additive SDA was applied using Eqs. (6–10). The chaining approach was adopted to minimize the temporal aggregate effect in the SDA results (Su and Ang, 2012b). The additive decomposition results for normal exports and processing exports are shown in Fig. 5(a) and 5(b), respectively.

The overall patterns of the driving forces throughout the period are very similar for normal exports and processing exports. Among the five driving factors discussed in Eqs. (6–10), energy efficiency improvement played the key role in reducing the embodied energy in trade, while final demand total effects contributed the most to the increase

of embodied energy. In comparison, the other three effects are relatively small in magnitude and have much less influence on the embodied energy. It is also noted that the total processing exports declined earlier in 2008, but total normal exports declined later in 2009. For normal exports, the final demand total effect generally outperformed the energy intensity effect, so that the embodied energy displays upward trends in the prior- and post-crisis sub-periods and a plunge in 2009. Interestingly, the plunge was not only due to the final demand total effect but also the energy intensity effect. For processing exports, the two effects almost offset each other, which makes the embodied energy in processing exports stable.

From Eq. (3), the energy intensity effect for embodied energy changes in normal exports was determined by the energy intensity improvement ($f_{v,d}$) in the domestic use/normal exports only. However, the energy intensity effect for embodied energy changes in processing exports came from both the energy intensity improvements in the domestic use/normal exports ($f_{v,d}$) and in the processing exports production ($f_{v,p}$). It was found that more than 75% of the total energy intensity effects for processing exports came from energy efficiency improvements in $f_{v,d}$.

Among the 36 sector classifications, the largest contributing sectors for energy efficiency improvement were sector “S13-Basic metals”, sector “S10-Chemicals and pharmaceutical products”, sector “S21-Electricity, gas, water supply” and sector “S24-Transportation and storage”. Their energy efficiency improvements accounted for more than 70% of the total energy efficiency improvements during the 2005–2015 period. Particularly, sector “S13-Basic metals” alone contributed to around 38% of the total energy efficiency improvement. However, these major contributing sectors also experienced some occasional increases in energy intensity, such as the sector “S13-Basic metals” in 2007–2008 and 2012–2013, “S21-Electricity, gas, water supply” in 2007–2008.

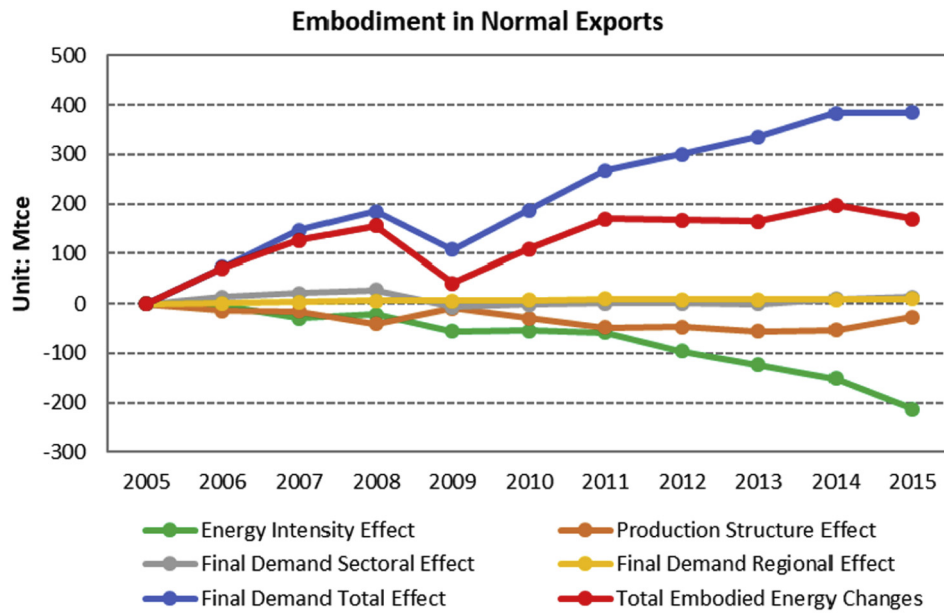
3.4. China's aggregate embodied energy intensity in Trade, 2005–2015

The embodied value added in normal and processing exports for the 2005–2015 period can be obtained using the Eq. (11). The aggregate embodied intensity (AEI) defined in Section 2 to evaluate the contribution of exports to embodied energy relative to their contributions to value added (or GDP) can be calculated using the Eq. (14). The AEI values for normal and processing exports and their contributions to national aggregate intensity (AI) in China are given in Fig. 6. The share of embodied value added in exports by major sectors and major trading partners are given in Figs. 7 and 8 respectively (detailed sectoral and regional names are given in Tables A1 and A2 in Appendix A). Similar to Figs. 3 and 4, the sectoral and regional classifications were grouped into 20 sectors/regions for ease of illustration.

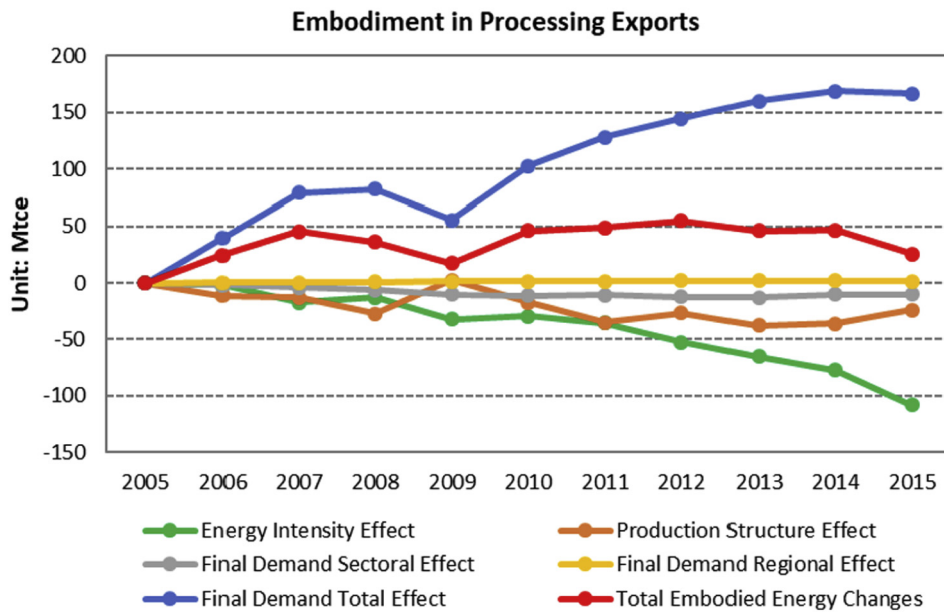
From Fig. 6, the over trend shows that the AEI in normal exports and processing exports persistently decreased over the entire period of study. For example, the AEI in normal exports declined by 38% (from 0.1213 tce/1000 RMB to 0.0756 tce/1000 RMB), while the AEI in processing exports decreased by 45% (from 0.1084 tce/1000 RMB to 0.0593 tce/1000 RMB) during period 2005–2015. Particularly, the AEI in normal exports experienced a huge decline around the global financial crisis, from 0.1167 tce/1000 RMB in 2008 to 0.1015 tce/1000 RMB in 2009. From their contributions to national aggregate intensity, the contribution of normal exports firstly increased from 2005 to 2008, dropped in 2009, and then became quite stable after 2010. In contrast, the contribution of processing exports increased consistently during the 2005–2015 period.

As explained in Su and Ang (2017), the AEI in exports can be represented as the weighted sum of the sectoral AEI, where the weights are the share of sectoral embodied value added. From normal exports as shown in Fig. 7(a), the value added or GDP was mainly generated from the demands in sectors “S06-Textiles, wearing apparel, leather and related products” (17%–20%), “S17-Machinery and equipment” (8%–11%), “S13-Basic metals” (6%–12%), and “S10-Chemicals and

⁵ For regional results in Figure 4, only China's largest 19 bilateral trading partners are included, while the rest are grouped into the rest of the world (or ROW)



(a) Normal exports



(b) Processing exports

Fig. 5. Results of the additive SDA of China's embodied energy changes, 2005–2015.

pharmaceutical products" (6%–8%). The global financial crisis decreased the share in sector "S13-Basic metals" significantly from 11.9% in 2008 to 6.0% in 2009, leaving the share in sector "S06-Textiles, wearing apparel, leather and related products" and "S20-Other manufacturing" relatively increased.

For processing exports as shown in Fig. 7(b), the value added or GDP was mainly generated from the demands in sectors "S15-Computer, electronic and optical products" (41%–49%), "S06-Textiles, wearing apparel, leather and related products" (7%–15%), and "S16-Electrical equipment" (11%–15%). Among these major sectors, there was a shift from "S06-Textiles, wearing apparel, leather and related products" to

sectors "S15-Computer, electronic and optical products" and "S16-Electrical equipment".

From Eqs. (12) and (13), the AEI in exports can also be represented as the weighted sum of the AEI in bilateral trade with the trading partners, where the weights are the share of regional embodied value added. As shown in Fig. 8(a), the major contributors to value added or GDP embodied in normal exports were from bilateral trade with the United States (19%–27%), Japan (8%–14%) and Korea (5%–7%). Most of the regional share decreased after the global financial crisis, but the share of the United States dropped earlier from 24.0% in 2007 to 21.7% in 2008. Fig. 8(b) shows that the major contributors to value added or

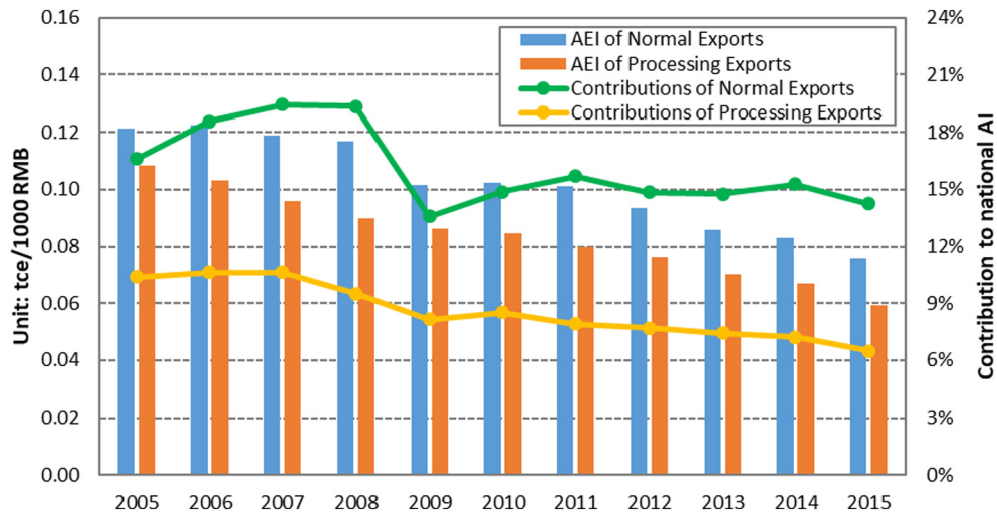


Fig. 6. China's aggregate embodied energy intensity in exports and their contributions to national aggregate energy intensity, 2005–2015.

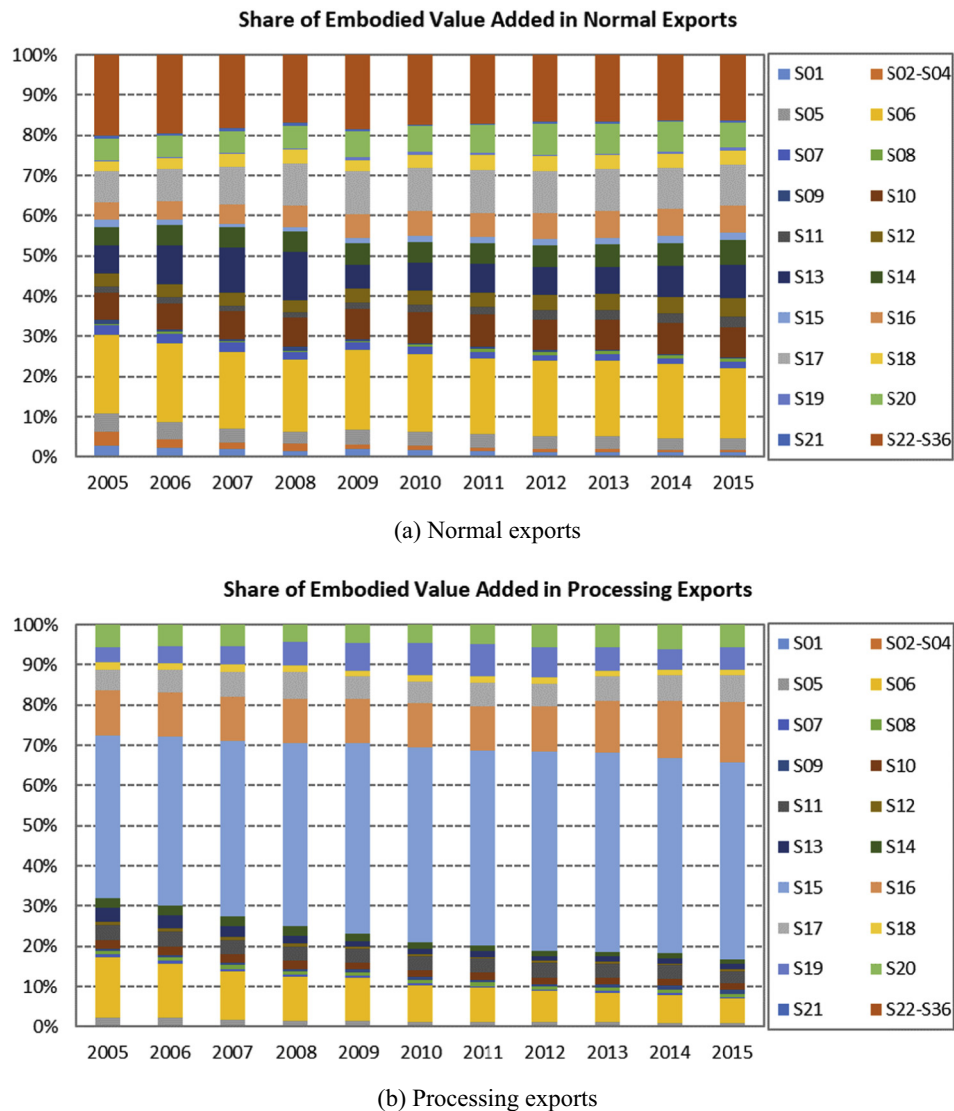


Fig. 7. Share of China's embodied value added in exports by major sectors, 2005–2015. (Note: The detailed sector names are given in Table A.1 in Appendix A, and the detailed results of the plots can be found in the supplemental data file).

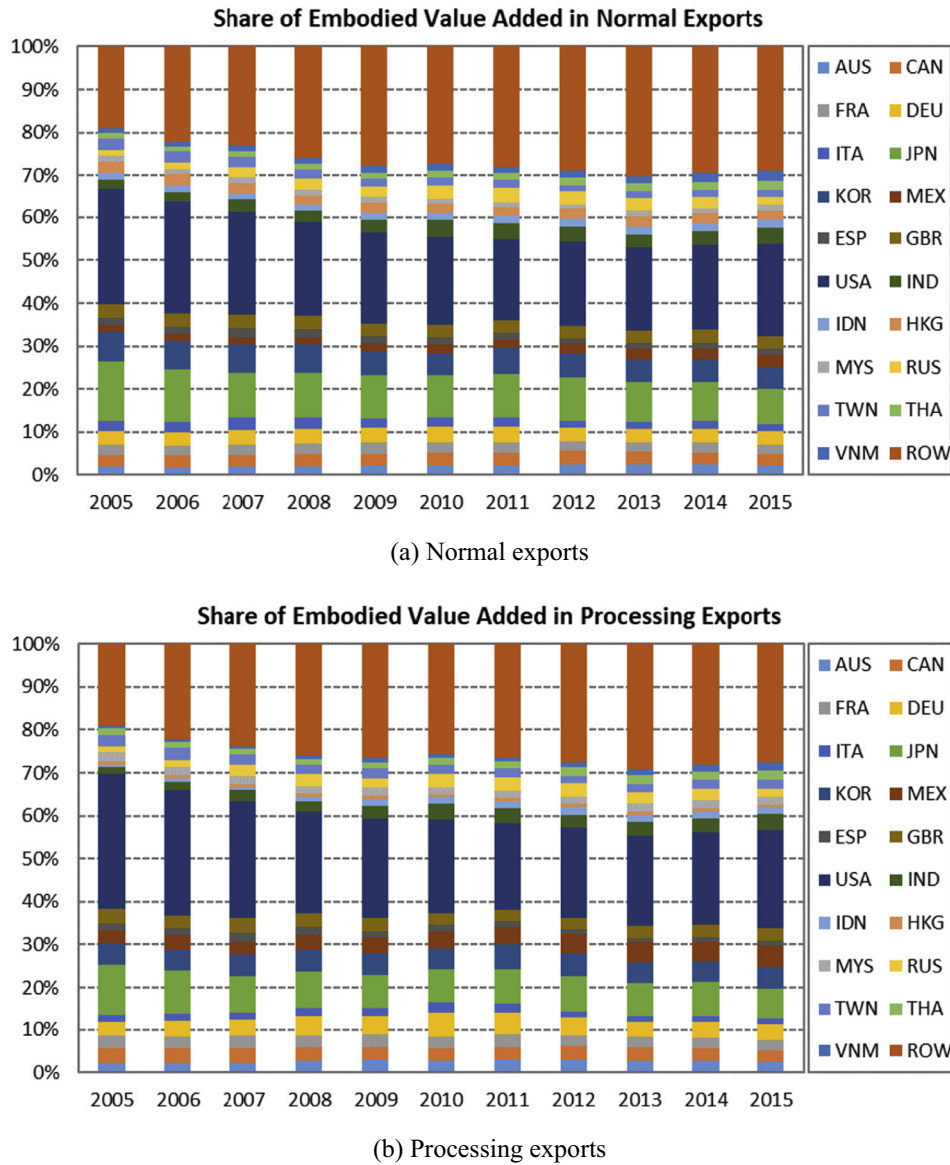


Fig. 8. Share of China's embodied value added in exports with its major trading partners, 2005–2015 (Note: The detailed region names are given in Table A.2 in Appendix A, and the detailed results of the plots can be found in the supplemental data file).

GDP embodied in processing exports were from bilateral trade with the United States (20%–31%), Japan (7%–12%), Korea (5%–6%) and Germany (3%–6%). Similar as the embodied energy, there was significant shifts from the United States and Japan to other economies in the rest of the world.

3.5. Multiplicative SDA of aggregate embodied energy intensity changes, 2005–2015

The AEI changes discussed in Section 3.4 were the net impact of many driving factors, although the energy efficiency improvement is supposed to be the key factor. To isolate the impacts of individual driving forces, multiplicative SDA was applied using Eqs. (16–19). The chaining approach was adopted to minimize the temporal aggregate effect in the SDA results (Su and Ang, 2012b). For ease of illustration in the figures, the logarithm of the multiplicative decomposition results for normal and processing exports are shown in Fig. 9(a) and 9(b), respectively.

The overall patterns behind the driving forces to AEI changes were quite similar for normal and processing exports throughout the studying period. Among the four driving factors discussed in Eqs. (16–19), the largest contributor was the energy efficiency improvement, followed by the production structure optimization. The AEI of normal exports declined substantially in 2009 mainly due to the combined energy intensity effect and final demand sectoral effect, whereas the AEI of processing exports declined smoothly over time as the production structure effect largely offset the energy intensity effect in 2009.

Energy efficiency improvements among 36 sectors were found to be similar to the results of the additive SDA in Section 3.3. The largest four contributing sectors were “S13-Basic metals”, “S10-Chemicals and pharmaceutical products”, “S21-Electricity, gas, water supply” and “S24-Transportation and storage”. Their energy efficiency improvements helped to reduce around 30% of the AEI of normal exports and processing exports during the 2005–2015 period. Particularly, sector “S13-Basic metals” alone contributed to around 16% of AEI reduction. The largest energy efficiency improvements by sector “S13-Basic metals” happened in periods 2008–2009, 2011–2012 and 2014–2015.

3.6. Comparisons with previous studies

This paper is an extension of the time-series study on embodied emissions in process trade in [Su and Thomson \(2016\)](#) and the national AEI framework proposed in [Su and Ang \(2017\)](#). [Su and Thomson \(2016\)](#) is the first study to provide the time-series estimates of embodied emissions only in China's normal/processing exports for 2006–2012. In contrast, this paper analyzes not only embodied energy but also embodied energy intensity in normal/processing exports for 2005–2015. The embodied energy and embodied emissions analyzed in these two

studies are not the same. Their differences mainly come from the fuel mix in final energy consumption by sector ([Su et al., 2017](#)) and emission intensity in power generation due to generation efficiency and generation mix ([Ang and Su, 2016](#)).

In the literature, some studies have calculated the AEI of energy/emissions in normal/process exports for selected years, such as [Dietzenbacher et al. \(2012\)](#) and [Liu et al., 2016b](#) on AEI of emissions in exports for 2002 and 2007, and [Jiang et al. \(2015a\)](#) on AEI of energy in exports for 2007. There is no relationship between the AEI in exports and national AEI or sectoral AEI reported in previous studies, until the

national AEI framework developed in Su and Ang (2017). This study (Section 2.3) is the extension of national AEI framework from traditional I-O model to extended I-O model with processing trade. The multiplicative SDA analysis is further combined with the AEI indicators using extended I-O model to investigate the driving forces to their changes over time.

In previous energy/emission studies using extended I-O model with processing trade, very few study decompose the normal/processing exports into their bilateral trade with China's major trading partners due to the complexity in data processing. With the OECD-ICIO database, this study analyzes the embodied energy and intensity flows in China's bilateral trade in both normal and processing exports by sector and major trading partners. More detailed results on embodied energy and intensity flows and their driving forces have been discussed in previous subsections in Section 3.

4. Discussion and conclusions

This paper is an extension of the studies by Su and Thomson (2016) and Su and Ang (2017). It analyzed China's embodied energy and intensity in both normal and processing exports during the 2005–2015 period, and applied SDA techniques to delineate the driving forces behind the changing embodiments over the study period. The empirical study highlights the importance to use the extended I-O model to analyze embodied energy and intensity in trade, especially when processing exports account for around half of China's total exports. The study period covers the 11th Five Year Plan (2006–2010) period, the global financial crisis (2007–2008) and the recovering period after 2010, and the 12th Five Year Plan (2011–2015) period. Overall speaking, the energy efficiency improvements played the most important role in reducing China's embodied energy in trade, greatly offsetting the increasing demands for China's goods and services from other countries, and improving China's aggregate embodied energy intensity in trade. The findings are useful for the Chinese government to evaluate the energy targets settings for the coming 14th Five Year Plan (2021–2025) and medium-term energy planning to achieve its emission target and sustainable development by 2030.

Prosperous international trade has brought countries closer than before, enhancing different countries' specialization areas in the regional and global supply chains, and also contributed to reducing unbalanced resource distributions among world countries. At the same time, the "leakage" phenomenon through embodied energy in trade will continue, and most likely will increase. With a global thirst for energy, it is of key importance to evaluate the costs and benefits of such leakages, especially when designing national energy saving policies and studying the energy security issues for a country, especially during the US-China trade war and COVID-19 periods. One of the key findings from this paper is that China contributed around 500–800 Mtce of energy each year during the period 2005–2015 through its exports (especially the normal exports) to other countries. As developed countries are the major end uses of embodied energy from developing countries, it is essential for developed countries to help energy conservation in the developing countries through technology transfer and investment in energy efficiency technologies. Ultimately, this will also help reducing the global carbon emissions, and combating the climate change issues.

International trade not only drives the energy use in the production, but also help creates the value added (or GDP) to the country. From demand side, the aggregate embodied intensity (AEI) of energy in trade can be used to evaluate the relative effectiveness of energy consumption and value added (or GDP) generation. The empirical results of this paper show that the AEI in normal exports and processing exports together contributed to around 22% of national aggregate energy intensity after global financial crisis. As the AEI in trade is the weighted sum of the sectoral AEI, the largest three sectors, i.e. sector "S06-Textiles, wearing apparel, leather and related products", "S13-Basic metals" and "S17-Machinery and equipment", accounted for around 40% of the AEI in

normal exports; in contrast, the largest three sectors, i.e. "S06-Textiles, wearing apparel, leather and related products", "S15-Computer, electronic and optical products" and "S16-Electrical equipment", contributed to more than 60% of the AEI in processing exports. To further reduce the AEI in trade, Chinese government can focus on these essential sectors through improving the energy efficiency and/or enhancing the value chain in the upstream industries (Su et al., 2019). This will become increasingly important when designing China's international trade policy with world countries, especially during the post COVID-19 period.

China's exports are mainly driven by the demands from the United States, Japan and Korea. With China's trade diversification after global financial crisis, their total share of embodied energy in bilateral trade had dropped from 46%–47% in 2005 to 33%–34% in 2015. At the same time, their total contributions to China's AEI in trade also declined from around 48% in 2005 to around 35% in 2015. From embodied energy and intensity perspective, there was a shift of embodiments in bilateral trade from the developed countries to the developing countries (such as Brazil, Mexico, India, and ASEAN region). With the launch of the Belt and Road Initiative (BRI) by Chinese government in 2013, the trade diversification will continue as the increase of future demands will mainly come from the developing countries. To achieve sustainable development, it is a good opportunity for the enterprises in China to improve their productivities, optimize their business structures, and upgrade their positions along the regional and global value chain.

Due to data limitations, there are very few studies focusing on embodied energy flows and SDA studies using the time-series data differentiating normal and processing exports. This paper used the time-series (2005–2015) extended I-O tables compiled in the OECD-ICIO database to investigate China's embodied energy flows in its normal and processing exports. Su and Thomson (2016) compiled its own time-series (2006–2012) extended I-O tables for China and analysed its embodied emissions in normal and processing trade. Both this study and Su and Thomson (2016) adopted the SDA technique to understand the driving forces behind the embodiment changes happened. This is an area deserving of further investigation as some forms of processing trade can be found in many countries/regions. Taking China for example, processing exports mainly happen in some eastern regions, like Guangdong, Fujian and Jiangsu provinces. To better support the regional development and policy making, it is valuable to use the extended I-O framework with processing trade in the empirical analysis. Some possible future research includes (a) applying the similar analysis framework to other indicators, such as GHG emissions, water and air pollutant; (b) disaggregating China as a whole into different regions to capture the regional supply chain and feedback effects (Su and Ang, 2011, 2014b) and/or including China into the global supply chain (Su and Ang, 2010; Wang et al., 2017b; Yang and Su, 2019); and (c) investigating different embodiment performances of normal and processing exports in different regions or countries using the spatial decomposition techniques⁶ (Su and Ang, 2016; Yan and Su, 2020b).

Acknowledgements

Our heartfelt thanks should be given to the National Natural Science Foundation of China (71771105, 71974077, and 71834003), National Philosophy and Social Science Foundation of China (16ZZD049), Guangdong Young Zhujiang Scholar (Yue Jiaoshi [2016]95), Guangdong Key Base of Humanities and Social Science—Enterprise Development Research, and Guangzhou key Base of Humanities and Social Science—Centre for Low Carbon Economic Research for funding supports.

⁶ Traditional decomposition is conducted over time, i.e. temporal decomposition analysis. The analysis can also be conducted to study the variations of an aggregate indicator between region/countries at a certain time point, i.e. spatial decomposition analysis. Spatial IDA framework can be found in Ang et al. (2015, 2016), while spatial SDA framework is given in Su and Ang et al. (2016).

Appendix A. Sectoral and regional classifications

Table A.1

Sectoral classification in the OECD-ICIO database.

| Sector ID | Sector name |
|-----------|--|
| S01 | Agriculture, forestry and fishing |
| S02 | Mining and extraction of energy producing products |
| S03 | Mining and quarrying of non-energy producing products |
| S04 | Mining support service activities |
| S05 | Food products, beverages and tobacco |
| S06 | Textiles, wearing apparel, leather and related products |
| S07 | Wood and products of wood and cork |
| S08 | Paper products and printing |
| S09 | Coke and refined petroleum products |
| S10 | Chemicals and pharmaceutical products |
| S11 | Rubber and plastic products |
| S12 | Other non-metallic mineral products |
| S13 | Basic metals |
| S14 | Fabricated metal products |
| S15 | Computer, electronic and optical products |
| S16 | Electrical equipment |
| S17 | Machinery and equipment |
| S18 | Motor vehicles, trailers and semi-trailers |
| S19 | Other transport equipment |
| S20 | Other manufacturing; repair and installation of machinery and equipment |
| S21 | Electricity, gas, water supply, sewerage, waste and remediation services |
| S22 | Construction |
| S23 | Wholesale and retail trade; repair of motor vehicles |
| S24 | Transportation and storage |
| S25 | Accommodation and food services |
| S26 | Publishing, audiovisual and broadcasting activities |
| S27 | Telecommunications |
| S28 | IT and other information services |
| S29 | Financial and insurance activities |
| S30 | Real estate activities |
| S31 | Other business sector services |
| S32 | Public admin. and defence; compulsory social security |
| S33 | Education |
| S34 | Human health and social work |
| S35 | Arts, entertainment, recreation and other service activities |
| S36 | Private households with employed persons |

Table A.2

Regional classification in the OECD-ICIO database.

| Regional ID | Abbr. | Region name | Regional ID | Abbr. | Region name |
|-------------|-------|----------------|-------------|-------|--------------------|
| R01 | AUS | Australia | R34 | TUR | Turkey |
| R02 | AUT | Austria | R35 | GBR | United Kingdom |
| R03 | BEL | Belgium | R36 | USA | United States |
| R04 | CAN | Canada | R37 | ARG | Argentina |
| R05 | CHL | Chile | R38 | BRA | Brazil |
| R06 | CZE | Czech Republic | R39 | BRN | Brunei Darussalam |
| R07 | DNK | Denmark | R40 | BGR | Bulgaria |
| R08 | EST | Estonia | R41 | KHM | Cambodia |
| R09 | FIN | Finland | R42 | CHN | China |
| R10 | FRA | France | R43 | COL | Colombia |
| R11 | DEU | Germany | R44 | CRI | Costa Rica |
| R12 | GRC | Greece | R45 | HRV | Croatia |
| R13 | HUN | Hungary | R46 | CYP | Cyprus 2 |
| R14 | ISL | Iceland | R47 | IND | India |
| R15 | IRL | Ireland | R48 | IDN | Indonesia |
| R16 | ISR | Israel | R49 | HKG | Hong Kong, China |
| R17 | ITA | Italy | R50 | KAZ | Kazakhstan |
| R18 | JPN | Japan | R51 | MYS | Malaysia |
| R19 | KOR | Korea | R52 | MLT | Malta |
| R20 | LVA | Latvia | R53 | MAR | Morocco |
| R21 | LTU | Lithuania | R54 | PER | Peru |
| R22 | LUX | Luxembourg | R55 | PHL | Philippines |
| R23 | MEX | Mexico | R56 | ROU | Romania |
| R24 | NLD | Netherlands | R57 | RUS | Russian Federation |
| R25 | NZL | New Zealand | R58 | SAU | Saudi Arabia |
| R26 | NOR | Norway | R59 | SGP | Singapore |
| R27 | POL | Poland | R60 | ZAF | South Africa |

Table A.2 (continued)

| Regional ID | Abbr. | Region name | Regional ID | Abbr. | Region name |
|-------------|-------|-----------------|-------------|-------|-------------------|
| R28 | PRT | Portugal | R61 | TWN | Chinese Taipei |
| R29 | SVK | Slovak Republic | R62 | THA | Thailand |
| R30 | SVN | Slovenia | R63 | TUN | Tunisia |
| R31 | ESP | Spain | R64 | VNM | Viet Nam |
| R32 | SWE | Sweden | R65 | ROW | Rest of the World |
| R33 | CHE | Switzerland | | | |

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.eneco.2020.104911>.

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